

Stepping-up innovations in the water–energy–food nexus: A case study of anaerobic digestion in the UK

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Funding information

Engineering and Physical Sciences

Research Council, Grant/Award Number:

EP/N00583X/1

Grand societal challenges such as climate change, poverty and biodiversity loss call for rapid and radical changes to systems of production and consumption. Consequently, there is a growing interest in the dynamics of innovation, both social and technical, to accelerate innovation diffusion so as to increase the possibility of a step-change or large-scale transition. Research on the water–energy–food nexus adds an additional dimension to existing discussions, calling for transitions that recognise the sustainability challenges facing three major resource domains, and the synergies and tensions involved in their management. This paper examines anaerobic digestion (AD) – an example of innovation with potential benefits across the water–energy–food nexus – to understand the conditions that influence the rate of AD implementation and the achievement of its potential multi-sectoral benefits across the water–energy–food nexus. Interview data regarding 15 AD plants are examined alongside complementary data from interviews and workshops using the Technological Innovation Systems framework. This framework provides an analytical structure through which the processes that enable and constrain the implementation of AD in the UK can be examined, enabling the identification of potential mechanisms to support AD's wider and more effective deployment. The findings call for recognition of the unintended consequences of sectoral support mechanisms for technological adaptation, and consequent performance of AD in other resource domains and call for greater integration between policy mechanisms to enable AD to perform across the nexus. They also highlight a need to assimilate knowledge from multiple sources (including site-specific understanding gained from experimentation) to enhance the base on which policy and decision-making occurs. These findings contribute to existing literature on sustainable transitions by examining the complexities of multi-sectoral resource management in the context of nexus research.

KEYWORDS

climate change, integrated resource management, reflexive governance, resource scarcity, sustainable transition

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1 | INTRODUCTION

The nexus is becoming an important way of framing the challenges associated with meeting growing demands for water, energy and food. Its value lies in recognising the connections between different resource sectors and the cross-sectoral implications of management and innovation (Sharmina et al., 2016). However, integrated decision-making is inhibited by the breadth of individual resource domains, the various actors involved in each – and the consequent plurality of their visions for the future – combined with a tradition of siloed decision-making (Bazilian et al., 2011). Nexus research therefore adds an important element to discussions as it calls for joined-up responses that approach global challenges, such as poverty or climate change, afresh. Though not necessarily novel and by no means in itself a solution (Cairns & Krzywoszynska, 2016), the traction that nexus thinking has gained in policy circles gives cause for cautious optimism that the concept might offer a means of overcoming historical barriers to integrated management (Leck et al., 2015), and at the very least, provides a lens through which to examine the inter-dependencies between resource domains.

The existence of global challenges raises important questions about current systems of production and consumption, and calls for rapid and radical changes to human activity in every sector (Rockström et al., 2009). Technological innovations are of particular interest in these discussions, as they present opportunities for experimentation and learning that might disrupt problematic modes of production and consumption (Fam & Lopes, 2015). Some innovations offer benefits in all three nexus domains, addressing specific issues that each domain faces, as well as their overarching challenges. These innovations have intrinsic value to nexus research, as they present potential seeds of transformation aligned with the synergistic modes of management that nexus research endorses. However, successful innovation diffusion depends upon political processes and institutional structures (Geels & Raven, 2006), and the nexus adds additional complexity to existing studies of innovation as its calls into question processes and structures within three major resource sectors.

The aim of our study is to understand the processes that influence the rate of implementation and the efficacy of technologies in responding to the multiple challenges that cut across the water–energy–food (WEF) nexus. As an empirical case, we examine anaerobic digestion (AD), a technology with multiple benefits across water, energy and food domains (see Section 2.1). We use the technological innovation systems (TIS) framework to analyse the interactions between AD and the broader innovation systems. This posits that the speed, scale and quality of technological deployment are contingent upon several “functions”, including, for example, the diffusion of knowledge and the mobilisation of resources (Hekkert et al., 2007) (see Section 2.2). Using mixed methods (see Section 3), we examine how the implementation of AD in the UK has been shaped by these functions of innovation systems (see Section 4). This paper thereby contributes to academic research and real-world problem solving by enhancing our understanding of the systems that might enhance the rate and efficacy of technological deployment in the nexus space.

2 | BACKGROUND AND CONTEXT

2.1 | Case study: AD in the UK

Anaerobic digestion is a biochemical process whereby organic materials are converted into biogas (a mixture of methane and carbon dioxide) and digestate (an organic liquid fertiliser). AD plants process various feedstocks including municipal waste, food wastes, farm wastes and residues, and purpose grown crops (PGCs). From a nexus perspective, AD using wastes is particularly desirable as it offers multiple benefits across energy, food and water domains. First, as a waste-disposal route, AD avoids the costs and emissions associated with landfill or incineration (National Grid, 2016) and thereby helps to reduce the environmental impact of waste disposal by making use of embedded water, energy and nutrients in waste materials. Second, digestate provides a substitute for synthetic fertilisers, thereby avoiding the cost, resources and emissions associated with their production (WRAP, 2012). Further, if applied appropriately, digestate benefits soil structure and water retention on agricultural land, thereby reducing the environmental implications of food production and contributing positively to land and water management (WRAP, 2012). Third, biogas derived from AD is a substitute for natural gas and may be converted to transport fuel, providing a renewable energy source that can be deployed in sectors that are difficult to electrify to complement the UK’s decarbonisation agenda. Biogas can also be stored for timely conversion to electricity, which is useful in balancing fluctuating supply from intermittent renewables (Styles et al., 2016; Thrän et al., 2015).

There is substantial potential to increase AD deployment in the UK, and to further realise its benefits across the nexus. By mid-2016, 381 AD plants were operational in the UK (ADBA, 2016).¹ These plants treat approximately 11.1 Mt (megatonnes) of waste organic materials (ADBA (Anaerobic Digestion & Bioresources Association), 2016) with approximately 230 MW of installed energy capacity (WRAP, 2017). Though the output of digestate is difficult to ascertain, 11.1 Mt of

organic waste would produce approximately 9.5 Mt of digestate.² Looking forward, it has been estimated that if the remaining 17 Mt of organic material disposed of by other means were to be treated via AD, this could produce 35 terrawatt hours (TWh) of biomethane per annum and 14.5 Mt of digestate (National Grid, 2016). In addition, an estimated 90 Mt of farm waste could be processed via AD (Defra, 2010). These figures are speculative, but provide some indication of the potential contribution AD could make to managing the UK's energy, food and water.

However, there are various socio-economic and political challenges that compromise the realisation of AD's potential. For example, the future availability of organic waste streams is uncertain (WRAP (Waste & Resources Action Programme), 2017), dependent upon the practices of waste producers and subject to competition from other waste treatment options (Fisgativa et al., 2016). Such uncertainty is an issue for AD, as a steady supply of inputs is required. Consequently, PGCs provide a reliable and therefore attractive alternative to wastes. However, PGCs place additional demands on land, water and fertiliser (Gerbens-Leenes et al., 2009; Styles et al., 2016), and are therefore less desirable from a nexus perspective. There are also siting controversies that influence the efficacy of AD. For example, the emissions and costs associated with transporting waste mean that AD is most effective when positioned close to sites of waste production, particularly densely populated areas. Establishing plants in these areas can be more difficult, however, due to the price of land and planning considerations (Röder, 2016). We propose that AD deployment in the UK would benefit from further analysis of the social and political conditions that constrain, enable and direct the scale and speed of implementation.

2.2 | Understanding the dynamics of innovation in AD

To date, the political dimensions of AD deployment have received limited attention in the scientific literature. Some exceptions include Röder (2016), who established that although AD is commonly assessed in environmental and economic terms, the drivers of AD implementation are both more numerous and more complex than such evaluative metrics imply. Levidow and Papaioannou (2013) and Levidow et al. (2014) demonstrate the multiple policy visions in which AD is incorporated, including energy security, renewable materials, rural development and decarbonisation, illustrating how AD is framed as a solution to numerous social and environmental issues. However, Edwards et al. (2015) show that renewable energy targets remain by far the most prominent mechanism to incentivise AD deployment in the UK. This is problematic as dependency on support from a single sector can diminish the legitimacy of the technology in other sectors and negatively impact on its ability to attract further resources. Furthermore, framing AD as *only* contributing to energy-related objectives affects technological pathways (Markard et al., 2016), reducing the potential of the technology to perform against social and environmental objectives across the WEF nexus. Understanding the processes that shape and constrain AD innovation is therefore fundamental if its potential performance is to be realised.

Guidance for further enquiry can be found within the literature on sustainability transitions, particularly that relating to TIS. The TIS literature provides a framework through which to understand processes of inertia and change, and their effects on technologies (Markard et al., 2012; Schlaile et al., 2017). The “functions approach” is a specific permutation of the TIS approach, which identifies key processes that enable a technology to integrate effectively within the wider system. The functions approach therefore enables the identification of constraints on innovation processes and potential opportunities to facilitate diffusion (Bergek et al., 2008; Hekkert et al., 2007, 2011). Hekkert et al. (2007) identify seven key functions: entrepreneurial activities, knowledge development and diffusion, guidance of search, market formation, resource mobilisation and creation of legitimacy. These are summarised in Table 1, together with indicators of their presence.

Technological innovation systems approaches have been used to understand numerous technological systems, including AD and biogas (Markard et al., 2009, 2016; Negro & Hekkert, 2008). However, there are no identified studies that consider the dynamics of innovation in relation to nexus discussions. This study seeks to fill that gap by considering AD not as an energy technology but as a technology that addresses challenges across multiple resource domains, and one that raises questions about how innovation pathways are shaped through interactions within multiple resource management arenas.

In this paper, the TIS framework is used to examine the conditions of AD development in the UK and to consider what more is needed to expedite the realisation of AD's potential across the nexus. We focus on AD applications that utilise wastes arising within food supply chains, rather than the full range of AD applications. As will be shown, while ostensibly homogeneous, these applications are hugely diverse, and the heterogeneity of inputs, outputs, and outcomes – intended or otherwise – provides sufficient potential to offer insights on how innovation pathways are shaped, and the implications for AD's performance in the context of the nexus. Alternative applications of AD have different historical legacies and are embedded in different socio-technical and political systems, meaning that AD is not best understood as a single innovation. Wastewater applications, for example, are a notable absence from this analysis; however as a comparatively mature, large-scale application that is relatively exclusive in terms of participation, comparison across these cases is beyond the scope of this paper.

TABLE 1 Key functions of technological integration

Function and rationale	Typical indicators
<i>Entrepreneurial activities:</i> entrepreneurs convert knowledge into action to maximise business opportunities	The number and variety of new entrants, diversification activities, and experiments with new technologies and processes
<i>Knowledge development:</i> knowledge is a fundamental requirement for innovation processes	Research and development activities, patents, and investments
<i>Knowledge diffusion:</i> new knowledge must be shared effectively to inform policy, and to disseminate ideas and opportunities	Numbers of knowledge exchange activities (e.g., conferences, workshops) dedicated to a specific technology
<i>Guidance of the search:</i> the processes whereby innovations are selected and favoured by actors, over alternative options	Recognition of specific efforts to raise expectations about new technological developments
<i>Market formation:</i> for innovations to become established they must gain footholds in new and existing markets, competing alongside existing technologies	Market incentives to encourage deployment, and non-market incentives (e.g., environmental standards) that enhance the performance of new technologies in existing markets
<i>Resource mobilisation:</i> allocation of human, physical and financial resources are basic requirements for innovations to perform all other functions effectively	Difficult to map, however actors in the innovation system are best placed to understand the sufficiency of available resources
<i>Creation of legitimacy:</i> a new technology must accrue legitimacy so as to become part of, or overthrow, incumbent regimes	The formation and the actions of advocacy groups and networking organisations

Source: based on Hekkert et al. (2007).

3 | METHODOLOGY

Fieldwork was undertaken between August 2016 and April 2017. Two interviews were conducted with each of nine AD operators, providing data with regards to 15 AD plants in the UK. Sampling for interviews was strategic, designed to reflect the diversity of AD facilities in terms of application, maturity and capacity, thereby enabling analysis of the implications and challenges such diversity brings. One interview was carried out on site at the AD plant, enabling discussions to be situated in the physical environment (Evans & Jones, 2011) and allowing for the development of a tacit understanding of the arrangements of different AD plants and their role within a network of ancillary practices of production and consumption.

The second interview extended the scope of discussion to understand operators' personal experiences of AD implementation and operation, and to cross-examine themes emerging throughout the study. Both interviews were semi-structured, enabling participants to focus on themes they considered significant (Longhurst, 2009). Multiple rounds of interviewing enabled cross-examination between cases, and extended the breadth and detail of information obtained. Each interview was audio recorded and transcribed, with field notes detailing observational data obtained during site visits. A multi-disciplinary team carried out the analysis, however a single researcher conducted each interview to maintain a non-intrusive dialogue with interviewees.

Various complementary methods were used to validate and supplement the interview data. Additional interviews were conducted with representatives of regulatory and trade bodies involved in the broader landscape of AD in the UK. Two workshops were held, each with approximately 40 participants including practitioners, policy-makers and researchers. The workshops enabled collective discussion around the visions, challenges and opportunities within the industry. In addition, a literature review was conducted to enable the data collected in interviews and workshops to be validated, clarified and further explored.

4 | RESULTS

Anaerobic digestion already involves a range of technologies and processes, with plants designed around different feedstocks, and producing different outputs. Consequently, no two plants are exactly alike. Table 2 summarises the material differences between the facilities examined in this study, focusing on their throughput and outputs. However, it is worth noting that the diversity of AD extends beyond the physical characteristics of a facility; the varying integration of a facility within local systems of production and consumption, and overarching economic, institutional and infrastructural contexts, are indicated here by the breadth of feedstocks, and the uses of energy and digestate.

The inherent complexity of the nexus combined with the diversity of AD together raise an important question about how innovation can be accelerated in a manner that amplifies positive outcomes while minimising negative impacts. By drawing attention to constraints on innovation, analysis of TIS functions can highlight opportunities to support and

TABLE 2 Summary of 15 anaerobic digestion (AD) plant characteristics

Reference (abbreviation)	Description	Status	Feedstock		Energy generation		Digestate production ^a		
			Type	Input (tonnes/ annum)	Source	Capacity (MWh per annum)	Grid connected/ used on site	Estimated output (tonnes/annum)	Used on site (Y/N)
Community enterprise 1a (CE1a)	Low-cost, manually operated micro-AD plant sited in a community garden. Food waste, locally sourced. Outputs used on site; biogas to heat polytunnels and fertiliser for growing	Operational	Food waste	5.3	On site	Thermal: 1.75	On site	5	Y
Community enterprise 1b (CE1b)	Micro-AD sited at a café. Food waste from the café and local homes. Outputs used on site; biogas for cooking, digestate for growing food for the café. Surplus fertiliser is offered to the public	Operational	Food waste	15	On site and local collections	Thermal: 3.5	On site	14	Y
Community enterprise 1c (CE1c)	Micro-AD sited at a wholefoods factory with a forest garden. Outputs used on site; biogas converted to biomethane to fuel a delivery vehicle, fertiliser in garden	Cancelled	Food waste	44	On site	Thermal: 10.5	On site	42	Y
Community enterprise 1d (CE1d)	Small digester based at recycling plant. Multiple waste collection and digestate removal contracts. Grid connected, with capacity to convert biogas to biomethane for their collection vehicles	Stalled	Food waste	146	Commercial and domestic	Thermal: 35.0	On site	139	N

(Continues)

TABLE 2 (Continued)

Reference (abbreviation)	Description	Feedstock		Energy generation		Digestate production ^a			
		Status	Type	Input (tonnes/ annum)	Source	Capacity (MWh per annum)	Grid connected/ used on site	Estimated output (tonnes/annum)	Used on site (Y/N)
Entrepreneur 1a (E1a)	Modular AD plant on farm. Multiple specialist feedstock contracts (e.g., horse manure and brewery wastes). Energy and digestate used on site. Surplus energy sold to grid	Operational	Mixed waste	115	Commercial	Thermal: 32 Electric: 17	On site, surplus to grid	109	Y
Entrepreneur 1b (E1b)	Modular AD plant on a commercial site. Multiple commercial food waste contracts. Energy used on site (as combined heat and power [CHP] and transport fuel) with surplus sold to grid. Digestate stored on site for contracted users	Operational	Food waste	325	Commercial	Electric: 45	On site, surplus to grid	309	Unknown
Entrepreneur 1c (E1c)	Demonstration plant showcases a modular cover for slurry pits that collect rainwater and methane emissions to produce biogas	Demonstration	Farm waste	Unknown	On site	Unknown	On site	Unknown	Unknown
Entrepreneur 1d (E1d)	Demonstration plant showcases a modular, rapidly deployable digester that provides a localised waste management solution for humanitarian crises	Demonstration	Organic wastes	Unknown	On site	Unknown	On site	Unknown	N

(Continues)

TABLE 2 (Continued)

Reference (abbreviation)	Description	Feedstock			Energy generation		Digestate production ^a		
		Status	Type	Input (tonnes/ annum)	Source	Capacity (MWh per annum)	Grid connected/ used on site	Estimated output (tonnes/annum)	Used on site (Y/N)
Farm 1 (F1)	Small farm-based AD plant. Inputs from farm wastes with break crops used as a supplement. Electricity supplied to grid and digestate used on farm	Decommissioned	Farm waste and purpose grown crops (PGC)	1,500	On site	Electric: 438	Grid connected	1,425	N
Farm 2 (F2)	AD plant sited on a farm. Inputs from farm wastes with break crops used as a supplement. Electricity supplied to grid and digestate used on farm	In planning	Farm waste and PGC	N/A	On site	Electric and heat: 8,760	On site, surplus to grid	N/A	Y
Commercial 1 (C1)	Large AD plant maintaining multiple commercial food-waste contracts and various digestate removal contracts. Energy used on site (CHP) and sold to grid	Operational	Food waste	37,000	Commercial	Electric: 9,023 Thermal: 13,140	Grid connected	35,150	N
Commercial 2a (C2a)	Large commercial AD plant maintaining multiple municipal and commercial contracts for food-waste supply and digestate removal. Energy used on site (CHP) and sold to grid	Operational	Food waste	90,000	Municipal and commercial	Thermal: 35,040	Grid connected	85,500	N

(Continues)

TABLE 2 (Continued)

Reference (abbreviation)	Feedstock			Energy generation		Digestate production ^a			
	Description	Status	Type	Input (tonnes/ annum)	Source	Capacity (MWh per annum)	Grid connected/ used on site	Estimated output (tonnes/annum)	Used on site (Y/N)
Commercial 2b (C2b)	Large commercial AD plant maintaining multiple municipal and commercial contracts for food-waste supply and digestate removal. Energy used on site (CHP) and sold to grid	Operational	Food waste	160,000	Municipal and commercial	Electric: 43,800	Grid connected	152,000	N
Public-private partnership 1 (PPP1)	Large AD plant with a large municipal food waste contract, and multiple smaller contracts. Energy used on site (CHP) and sold to grid	Operational	Food waste	30,000	Municipal and commercial	Electric: 8,760	Grid connected	28,500	N
Public-private partnership 2 (PPP2)	Large commercial AD plant maintaining multiple commercial contracts for food-waste supply and digestate removal. Energy used on site (CHP) and sold to grid	Under construction	Food waste	40,000	Municipal and commercial	Electric: 21,024	Grid connected	38,000	N

^aDigestate output is approximate, calculated on the assumption it is 95% of the inputted feedstock.

accelerate innovation. Accordingly, an assessment follows of how the dynamics of AD diffusion are shaped by the seven functions of innovation systems (Table 1). Reference codes from Table 2 are inserted in parentheses to identify particular sources of information.

4.1 | Entrepreneurial activities

As Table 2 indicates, AD is a diverse sector and entrepreneurs have contributed considerably to experimenting with different technological assemblages in different contexts. Many actors were observed to participate in entrepreneurial activity, with different objectives. For example, for operators involved in large-scale waste management (C1, C2a, C2b, PPP1, PPP2), AD provides a supplement or augmentation to their existing operations, offering a means of addressing perceived deficiencies in their business models or enhancing their sustainability credentials. Subsequently, entrepreneurial activity is undertaken to refine AD, and to streamline up- and down-stream processes that enable AD to function most effectively. Though these activities may be self-serving, they enhance the performance of, and business case for, AD and thereby aid the sector as a whole by helping to increase the performance and application of ADs.

Several other respondents embarked on AD entrepreneurship to capitalise on the combination of AD value streams or to develop novel AD systems to solve specific waste management challenges on behalf of others (e.g., E1a). These actors contribute to AD deployment by undertaking activities perceived risky by other actors in pursuit of profit. For example, one interviewee (E1a) had developed a modular AD system to lease to farmers. In this way, the entrepreneur reduces the capital investment required by farmers to establish AD on site, and had financed the research and development to optimise a modular system for flexible farm use. By absorbing financial risks that other actors deem unacceptable, this entrepreneur was able to make AD accessible to a wider market, and also to make more ambitious changes in product design, each of which may enable the more rapid realisation of AD's potential across the nexus.

A further space for entrepreneurial activity is in the intermediation of planning and construction. Several interviewees were participating in this regard, and others made reference to individuals and organisations that aided their own AD installation. Lengthy lead times for installation were identified as a key constraint on AD development, ranging from several months (e.g., CE1) to five years (e.g., C1). This variation is explained by the greater complexity of planning and permissions associated with larger plants and their more complex supply chains. However, public engagement can also take considerable time and expertise to negotiate, particularly for smaller operators who are less experienced and have a smaller development team. Some AD operators acted as knowledge brokers (e.g., C1) or consultants (e.g., F1) to support new entrants in navigating the planning process, designing plants and accessing materials, or undertaking public engagement.

There has been a rapid acceleration of AD implementation in the last six to seven years in agricultural and commercial settings (BEIS, 2017a), suggesting healthy entrepreneurial activity. The findings from this study indicate that entrepreneurial activity serves two core purposes. First, it expedites the start-up process, which in turn reduces financial risk, accelerates the realisation of benefits and increases the accessibility of AD for potential operators. Second, experimentation led by entrepreneurs has enabled the adaptation of AD, rendering it applicable in a wider range of waste management contexts and enhancing its performance across WEF domains.

4.2 | Knowledge development

There is evidence of substantial knowledge development activity in the AD sector, undertaken by plant operators and by academic and non-academic scientific communities. Substantial advances have been made, particularly with regards to optimisation, but also the secondary processes required to extend the utility and performance of AD applications towards different objectives. In the first instance, optimisation refers to activities undertaken to increase the efficiency of AD operations. Plant operators play a particularly prominent role in optimisation, as site-level experiments are well suited to understanding how plants respond to different feedstocks, and how AD processes can be developed for mixed and changing feedstocks:

“We get a lot of enquiries about testing different feedstocks, and have developed a huge database with information [on their performance]” (E1a).

These experiments are supplemented by research efforts within the international scientific community, particularly focused on developing pre-processing and refinement techniques to increase performance and enhance the value of AD outputs.

Beyond the advancement of AD science itself, there are burgeoning efforts to understand the broader contribution of AD to the energy and agricultural sectors where AD's nexus benefits are most established. One key question identified by

workshop participants related to the role of AD in future energy systems. However, while energy output is a well researched field, research into AD's broader contribution to decarbonisation strategies (see Section 2.1) is less actively pursued, which workshop participants associated with the present lack of incentives for energy storage. Conversely substantial efforts are made by AD operators and the scientific community, often in collaboration, to understand further the potential value of digestate for agricultural use (e.g., Nicholson et al., 2016), and its potential applications beyond the agricultural sector (Rigby & Smith, 2011); this is supported by recent efforts to develop markets for digestate. These findings suggest that knowledge development activities, particularly applied to the nexus, relate to guidance of the search (see Section 4.4) and market formation (see Section 4.5).

Knowledge development is fundamental to increasing AD's performance with regards to the challenges that span the WEF nexus, particularly given rapid advances in, for example, soil science and climate change research that further our understanding of the interactions between nexus subsystems. However, research undertaken to enhance AD's performance across the nexus (e.g., with regards to soil management and food production), and to understand the new mechanisms (e.g., in finance) and techniques (e.g., bio-refinery) that might be required to realise AD's potential, remains uneven and poorly coordinated. Further coordination of research and development activities, and extension of support for cross-sectoral studies, may further increase the benefit of AD across the nexus.

4.3 | Knowledge diffusion

Though small, the AD research community in the UK is well connected, with networking facilitated by intermediaries including trade associations (e.g., Renewable Energy Association for AD and Biogas [REA Biogas] and the Anaerobic Digestion and Bioresources Association [ADBA]) and Research Networks (e.g., Anaerobic Digestion Network [ADNet]). These intermediaries connect researchers, practitioners and other stakeholders while also establishing links with the international business and research community, and there is tangible evidence of effective knowledge diffusion in the AD sector; for example, the establishment of the Biofertiliser Certification Scheme in 2007 and the publicly available specification (PAS) BSI PAS 110 in 2010 that aims to standardise and assure the quality of digestate for potential users (see Section 4.5 for discussion). However, several participants acknowledged constraints on knowledge diffusion activities. First, there are difficulties in translating scientific knowledge into practice, partly explained by the limited interaction between research institutions and practitioners, and partly due to the context specificity of knowledge within AD. For most operators, conferences and workshops were considered ineffective forums for knowledge exchange, as the generalised insights gleaned at these events poorly predicted the results of on-site experiments (C1, E1). In contrast, respondents highlighted the importance of demonstration plants and informal networking in aiding knowledge diffusion (C1). Several interviewees described knowledge exchange activities situated at their sites, open to interested members of the public, researchers and others interested in AD operation (F1&F2, C1&C2, CE1). Others were private, informal networks, such as regular meetings among farmers, which served as an efficient forum for knowledge diffusion among a trusted network of peers (F1, C1).

This analysis highlights that, in addition to establishing an integrated knowledge development agenda, there is a need to develop appropriate forums for knowledge diffusion. While events such as workshops and conferences are valuable, these should seek to engage a wider range of stakeholders from across different domains. Informal forums also provide opportunities for knowledge diffusion, although the difficulties in sharing learning between geographically distant knowledge brokers are apparent. Existing intermediaries appear well placed to further aid knowledge diffusion.

4.4 | Guidance of the search

Energy policy was the most commonly cited driving force for deployment, with UK-based policy incentives (e.g., the Renewable Heat Incentive and Feed-in Tariff) providing support for AD at all scales. However, these incentives also shape the development of AD; for example, by emphasising energy output, such mechanisms offer little to encourage energy storage, or flexible demand response (C2). Moreover, AD has evolved to favour feedstocks and digestion processes that maximise energy generation, with less regard for AD's wider potential (C1):

renewable energy support does mean that you miss out feedstocks with lower energy value – farm manure and slurry is the most obvious example, as your prime motivation would be reducing emissions, avoiding open storage, or producing a stable material to return to land. But that's not what policy supports, policy supports you producing energy. (Trade association representative)

Alongside energy policy, waste management policies have also benefitted AD, increasing the attractiveness of AD as an alternative means of waste disposal (C1&2, PPP1&2). The landfill tax has increased the separation of organic materials from domestic waste, thereby increasing the volume and quality of organic waste available to operators. However, it has also intensified competition for waste, and forced AD plants into reducing the amount they charge to process the waste:

When there were fewer AD plants, there was more waste available to be processed. We got a gate fee³ for it, and one thing that has changed is the reduction of gate fees. We'd always seen that coming, but there's a much more varied scale now and sometimes we pay for it. (C1)

Like the reduction in renewable energy incentives, declining gate fees compromise the financial viability of AD and though many respondents saw AD as a secondary manufacturing process (e.g., for chemicals), a land management technique or an opportunity for business diversification (e.g., C1, F1&2), these qualities of AD are not presently incentivised. Thus AD is exposed to competition from other renewable energy and waste disposal options, particularly Energy-from-Waste, despite the fact other options offer fewer nexus benefits.

The multiple interactions between AD and energy, food and water domains mean different actors hold different expectations of AD, and deploy AD in an endeavour to meet different objectives. Offering different support mechanisms such as the landfill tax and Renewable Heat Incentive propagate AD, lending the sector a degree of resilience that allows a greater number of individuals to experiment with AD in their business. However, incentives also constrain experimentation, prioritising certain objectives, and skew technological development towards these. Consequently, across the sector as a whole, AD has to date evolved primarily to maximise energy output and generate income from waste disposal, thereby prioritising throughput rather than quality (which, for example, is of greater importance in determining the downstream value of digestate). In order to deliver other aspects of AD's potential in the nexus (for example, to reduce reliance on synthetic fertilisers or chemicals), it is necessary to reconsider support mechanisms and develop policy conditions more conducive to a holistic nexus vision.

4.5 | Market formation

As discussed in Section 4.4, AD largely exists within low-carbon energy markets and there are questions regarding whether this is the appropriate home for AD support. However, alternative markets for AD and its outputs are as yet limited. The most obvious alternative is the digestate market, however there is little demand for digestate outside agriculture at present, and even in agriculture, digestate is not yet considered a viable replacement for synthetic fertilisers. This is due to the variable nutrient value of digestate from AD – a result of the variable characteristics of feedstock – and the costs associated with transporting and using digestate, which has a high water content and is therefore costly to move and store, and differs from synthetic fertilisers in its application. Identifying markets for digestate is particularly challenging for AD operators with limited on-site use for digestate (CE1&2), and especially for plants that produce digestate in large volumes (C1–3, PPP1&2). It is therefore a burden for many AD operators:

Digestate is the major issue for AD ... Some of the larger sites are giving it away for free or having to pay for it to be taken away. Only occasionally are they paid for it. (CE1)

While standardisation and certification improve markets for digestate (see Section 4.3), these require time to become established and trusted among users. Subsequently, although energy policy mechanisms have helped to create a market for AD, it can be argued that the paucity of markets for the full range of inputs and outputs constrains the development of AD to those applications that maximise energy production (reinforcing the effect described in Section 4.4). To accelerate implementation of AD and better achieve its potential benefit across the nexus, it is necessary to consider how to support alternative markets for AD outputs.

4.6 | Resource mobilisation

Anaerobic digestion plants require a reliable and consistent supply of feedstock in order to function. However, establishing and maintaining feedstock supplies was one resource mobilisation challenge that several operators identified, affecting the

viability of AD at a project level and the sector as a whole. For operators producing organic wastes on site (F1&2), reducing the effects of short-term fluctuations in feedstock was the principal challenge. Most other operators depend on establishing and maintaining feedstock supplies through formalised contracts with suppliers such as local authorities and local businesses (e.g., CE3, C1&2, PPP1&2). However, given the increasingly competitive nature of waste management, maintaining supply contracts and their value (see Section 4.4) is a substantial challenge (F1, CE1). For several operators, simply maintaining contracts required considerable human resources to develop the relationships and manage logistical arrangements. The availability of human resources varied among AD operators, and was particularly challenging for operators dependent upon volunteers (CE1a&b), or for whom AD was an additional production practice to those already requiring their time and resources (F2). For larger plants, the facilities, resources and labour costs associated with processing waste were substantial (e.g., to separate organic matter from packaging [C1&2]).

Another identified constraint is access to financial resources. For operators of large AD facilities, external finance is commonly sought in the form of a loan (F2). For operators of smaller plants, funding came from a range of sources, including government grants (E4), charitable donations (CE1) and personal investment (F1). The diversity of funding streams reflects the diversity of project scale and objective. However, several participants voiced concerns regarding how financial resources for AD will be accessed in the future.

Technological diffusion can be delayed by difficulties in mobilising resources. However, this case illustrates how AD is dependent on resources across multiple resource domains. While a TIS perspective can highlight such bottlenecks, it does little to consider the relative impacts of resolving resource mobilisation obstacles. For example, though dedicated biocrops would provide a uniform feedstock, and bridge occasional gaps in feedstock supplies, nexus research highlights their implications for land and water resources, and the potential environmental and economic implications for the agri-food sector (see Section 2.1). In contrast, though there are challenges associated with collecting household organic wastes and ensuring the quality of this feedstock, the cross-sectoral benefits justify further consideration as to how household organic waste collection might be increased. Ensuring that innovations such as AD accelerate in a sustainable manner therefore requires an understanding of how such processes interact with resource flows across systems.

4.7 | Creation of legitimacy

Best described as the extent to which a technology is perceived to align with institutional structures and objectives, legitimacy underpins all other functions of the TIS. As Markard et al. summarise:

A technology that is well understood, compatible with established practices, socially accepted and perhaps even endorsed by regulation, possesses a high degree of legitimacy, which is essential for resource mobilization and successful development. (Markard et al., 2016)

The analysis presented in this paper demonstrates that AD aligns with the understandings, practices, norms and regulations of multiple resource sectors across the nexus. We therefore suggest that there are multiple institutional spaces in which legitimacy might be gained, or lost, affecting the rate and scale of AD innovation. The dynamics of AD's legitimacy have to date been most clearly narrated with regards to the energy sector (e.g., Markard et al., 2016 in the context of German bioenergy) where, with AD positioned as a valuable component of agendas around the decarbonisation of electricity and heat, resources have effectively been mobilised to support technological innovation in favour of maximising energy output from AD. The primary threat to legitimacy in the energy sector stems from assumptions made about the resources embedded in different feedstocks, particularly fuel crops. However, the strength of AD's legitimacy within the energy sector has been sufficient to stimulate the realignment of institutional structures, for example in the form of regulations around sustainability criteria (BEIS, 2017b) and the tightening of industry guidelines (e.g., the AD Certification Scheme [ADCS] in 2017).

Less apparent, however, is how AD has accrued – or failed to accrue – legitimacy within the institutions that effect change in other resource domains. Throughout the previous sections evidence has been presented to illustrate how different actors deploy AD, and advocate on its behalf, in recognition of the contributions AD might make to socio-environmental objectives beyond energy. These advocates articulate different understandings of AD's potential compared with those situated in the energy sector, and relate its performance to different institutional structures and objectives. For example, most operators and trade bodies positioned AD as a waste-management mechanism that aligns with political objectives regarding the reduction of environmental impacts of landfill. Similarly, in agricultural settings, AD's performance aligns with objectives such as nutrient management, agricultural diversification and sustainable rural livelihoods. These pockets of legitimacy

support experimentation (e.g., see Section 4.1), but have yet to translate into institutional support sufficient to direct knowledge and technological development sufficiently to achieve non-energy objectives. Indeed, several interviewees saw AD's uptake to be limited by the lack of political recognition of its role in terms of contributing to non-energy policy objectives.

Examining legitimacy from a nexus perspective casts a critical eye over the role of policy coherence in advancing sustainability innovations. It is increasingly argued that coherence among policy instruments impacting upon innovation is important in working synergistically (and without contradiction) towards a common objective (e.g., Leck et al., 2015; Sharmina et al., 2016). However, while coherence may be desirable, this analysis shows that the legitimisation processes underpinning coherence are, in reality, inherently political. They are thus, as Nilsson et al. (2012) argue, more about the negotiation of competing interests and ideas than about the reconciliation of common interests, with power politics playing a more central role than rational decision-making. In summary, understanding the role of innovations such as AD is incumbent on engaging with their legitimacy, not for specific sectors, actors and policy objectives, but in terms of the alignment with institutions across multiple sectors.

5 | DISCUSSION AND CONCLUSION

Emerging global challenges call into question current modes of production and consumption, fuelling an ongoing interest in understanding how systems of energy, food and water provision might be otherwise configured. This paper enhances our understanding of technological diffusion in the context of multi-sectoral resource management challenges by applying the TIS framework to observe AD applications that utilise wastes arising throughout the agri-food system. Deceptively simple, AD is shown to envelop a diverse array of facilities (Table 2), which offer a variety of perceived benefits to various stakeholders involved in the implementation of AD. Such diversity presents both opportunities and obstacles for accelerating implementation:

First, while the versatility of AD suggests the existence of multiple opportunities to benefit water, energy and food domains, it seems unlikely that these can be realised given the currently limited range of policy instruments. Though renewable energy incentives have so far proven valuable in increasing the rate of AD deployment in the UK, they have also had implications for how AD has evolved, with consequences for how effectively AD performs against different social and environmental objectives. For example, while AD is a proven method for biogas generation, the capacity for energy storage and responsive supply is as yet limited, and its potential as a fertiliser production process is underexploited. These findings suggest that realising the potential of technological innovations across the WEF nexus requires recognition of the unintended consequences of political support mechanisms for technological adaptation, and a restructuring of incentives so that multi-sectoral benefits are realised.

Second, beyond incentives and regulations, the findings indicate other constraints on AD in the agri-food sector. An overarching research agenda that integrates knowledge development activities and identifies gaps in the knowledge base would be advantageous. This might usefully be guided by nexus research, as a means to enable boundary crossing between disciplines and scales, and to emphasise the synergies and tensions between different research agendas (Hoolohan et al., 2018). The formation of markets to support effective application of AD as a waste management and digestate production technique relies on these processes of knowledge development and diffusion, and may therefore be improved through closer communication between stakeholders. To support these activities, consideration might be paid to how to smooth the challenges of obtaining financial and human resources for AD development, and how to maximise the efficacy of feedstock collection. For innovation more broadly, these findings demonstrate the importance of situated practices of knowledge development and diffusion for technological adaptation, and the political and economic contexts with which knowledge development takes place. The findings thereby reiterate the importance of recognising and assimilating knowledge from multiple sources (including site-specific understanding gained from experimentation) to enhance the base on which policy and decision-making occurs.

Our consideration of AD deployment in the context of the nexus complements the literature on innovation systems, where studies ordinarily focus on innovation(s) within a single resource domain (e.g., energy). Nexus thinking compels the analyst to examine in depth the interactions between resource domains, in this case carried out by investigating their manifestation in specific innovation experiments. The granularity of this case study affords insights into the micro-politics and context-specific practices that shape the adoption, adaptation and diffusion of innovation, and the implications for the performance of innovations across nexus domains. Detailed empirical analysis such as this is atypical within the transitions literature and, though messy, would seem essential to elucidating the contingencies of sustainable innovations, alongside

macro-level analysis of the processes of change. This is not to devalue general insights, but it suggests that innovation studies could do more to embrace the complexities inherent in the systems that they examine.

Finally, these findings support calls from within the transitions literature for more integrative and reflexive modes of transition management which are able to consider the interplay between resource domains. In highlighting the importance of looking beyond the boundaries of a single sector, they demonstrate how the challenges associated with single sector sustainability transitions (e.g., reconciling conflicts amongst policy mechanisms and planning tools) are amplified when considering the role of innovation across multiple sectors. The findings therefore suggest that further work is required to expand whole system perspectives to account for the multiple links between water, energy and food.

ACKNOWLEDGEMENTS

Funded by EPSRC Research Grant EP/N00583X/1 with sincere thanks to all interviewees and workshop participants who gave their time. We also thank the Editor and two anonymous reviewers for their assistance in drafting this article.

ENDNOTES

¹ Excluding the application of AD in wastewater treatment.

² WRAP (2012) estimate that the volume of digestate will be approximately 85% of the feedstock volume.

³ The charge levied by an AD plant to the waste management company to take the waste that is to be processed.

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How to cite this article: Hoolohan C, Soutar I, Suckling J, Druckman A, Larkin A, McLachlan C. Stepping-up innovations in the water–energy–food nexus: A case study of anaerobic digestion in the UK. *Geogr J*. 2018;00:1–15. <https://doi.org/10.1111/geoj.12259>